Welding Procedure Qualification of A36 Steel Plates Using the GTAW and GMAW Processes

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June 9th, 2016

MATERIALS
ENGINEERING
California Polytechnic State University

Table of Contents

List of Figures

List of Tables

1. Abstract

The purpose of this project was to qualify welding procedure specifications for the Las Positas College welding program using A36 steel in accordance with American Welding Society (AWS) D1.1, B4.0, and B2.1. Qualification was to be performed using both 1G (flat) and 3G (vertical) positions for Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) processes. Required qualification procedures included two face and two root bend tests coupled with a visual inspection for cracks within the weld region greater than ⅛" long, along with two reduced section tensile tests to ensure the tensile strength exceeded 58 ksi if the sample broke within the weld region or 55.1 ksi if the sample broke outside of the weld region. Tests were standardized by using American Society for Testing and Materials (ASTM) standards. Cracks greater than 1/8" were found in the weld region of bend tested samples in each process except for the 3G GTAW, disqualifying them. The failed samples were broken open at the crack and examined using optical microscopy in conjunction with polarized light as well as stereo microscopy to determine the inclusion and porosity content of the base and weld metal. The microscopic examination revealed a high degree of porosity and a lack of fusion in a 1G GTAW root bent sample as indicated by the presence of back gouging marks found in the areas of the weld having lack of fusion. This was the result of improper back gouging procedures. Microscopic examinations of GMAW fracture surfaces showed signs of heavy oxidation and inclusion content within the weld metal as well as a lack of fusion between the weld passes. Both 3G GTAW samples passed tensile tests with tensile strengths greater than 64 ksi, and the 3G GTAW process was therefore qualified.

2. Literature Review

2.1 Introduction

Welding Procedure Specifications are written, qualified welding procedures that provide direction for making production welds to code requirements. Completed WPSs describe all essential and nonessential variables per welding process used in the WPS.[1] An example WPS can be seen in Appendix A. The necessary variables that must be met are in accordance with a set of standards that have been written and published; in this case the standards were written by the American Welding Society. After being written, a WPS typically must be qualified by a number of mechanical tests and visual inspections that are required by the AWS D1.1 and B4.0 standards and defined by ASTM E190-14 and A370-15. The results of the test are written in a Procedure Qualification Record (PQR), which is later attached to the WPS to notify the welder that the WPS has been qualified and can be followed to perform welds and certify welders. An example PQR can be seen in Appendix B. The list of process/base material/position combinations evaluated in this project are summarized in Table I.

Table I. Process/Base Material/Position Combination of Welding Procedure Specifications

Process	Base Material	Position
Gas Metal Arc Welding	A36 Steel	1G (Flat)
Gas Metal Arc Welding	A36 Steel	3G (Vertical)
Gas Tungsten Arc Welding	A36 Steel	1G (Flat)
Gas Tungsten Arc Welding	A36 Steel	3G (Vertical)

WPSs consist of essential variables and nonessential variables. Essential variables are factors that cannot be changed in the specification without the specification having to be requalified. The essential variables in this project include:[2]

- Welding Process
- Base Metal
- Filler Metal
- Electrode
- Position
- Shielding Gas
- Gas Flow Rate
- Preheat and Interpass Temperatures
- Post-weld Heat Treatment

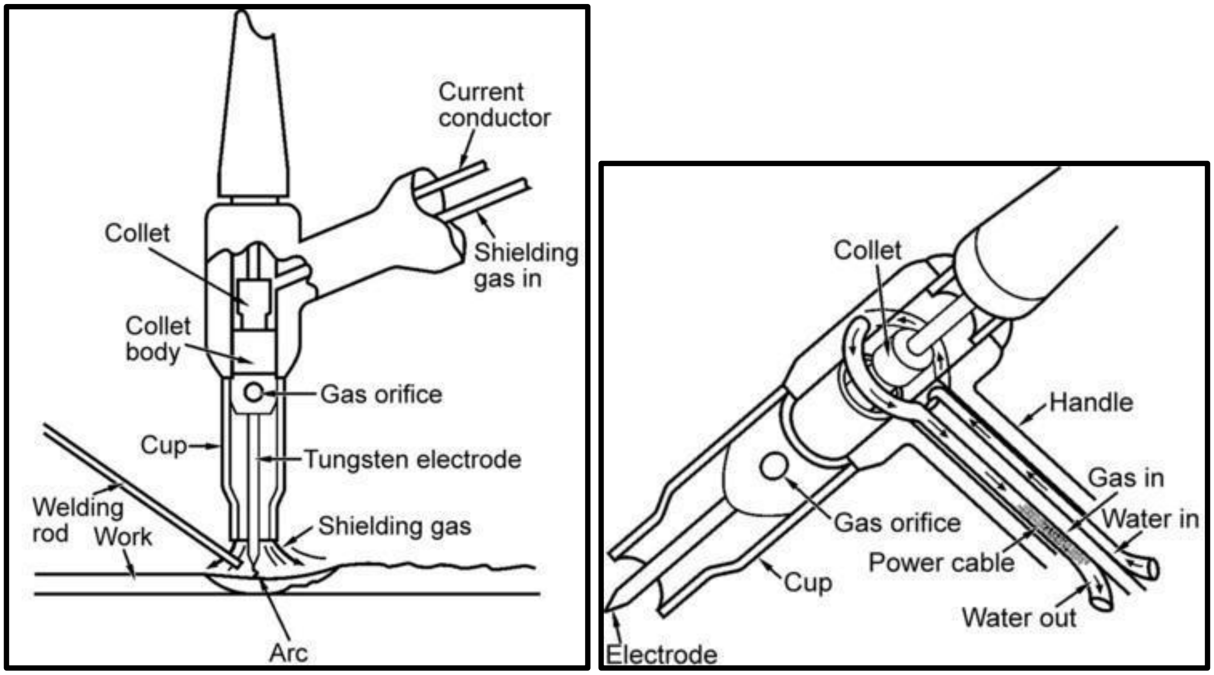
Nonessential variables are parameters in the WPS that can be changed without the need for requalification. However, a nonessential variable for one process may be an essential variable for another. Examples of nonessential variables include:[2]

- Supplied Voltage
- Supplied Amperage
- Travel Speed
- Some Joint Designs

2.1.1 Welding Processes for Welding Procedure Qualification

The gas welding processes used in the project were: Gas Tungsten-Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW).

Gas Tungsten-Arc Welding is an arc welding process that maintains an electric arc struck between a tungsten electrode and a metal workpiece which provides the necessary heat for the welding process. The weld zone is protected from atmospheric contaminants by a shielding gas fed through the welding torch. This prevents the weld from becoming porous and weakened by the oxygen, nitrogen, and other gases and other vapors present in the atmosphere. Argon and helium are the typical gases used for GTAW, although argon is usually preferred because of its suitability for a wide variety of metals, the lower flow rates required, and its better arc stability.[3] Either a DC or AC power supply may be used for GTAW. The DC welding circuit may be hooked up in either straight polarity (dcsp) or reverse polarity (dcrp). In dcsp, the electrons flow from the electrode to the plate and hit at a high velocity which exerts a high heating effect on the plate. This forms a narrow weld with deep penetration. However, in dcrp, the electrode receives the extra heat which tends to melt off the end of the electrode. As a result, a larger diameter electrode is required for dcrp welding. Furthermore, the increased size of the electrode and lower current forms a wide weld with shallow penetration. The AC welding circuit is a combination of dcsp and dcrp. It is a common practice to superimpose a high-voltage, high-frequency, low-power current on the AC welding current to compensate for any oxide film that could form on the metal workpiece. The GTAW process uses nonconsumable, tungsten electrodes that may be pure tungsten or thoriated, zirconiated, ceriated or lanthanated tungsten. The current carrying capacity of the electrode increases as the size of the electrode diameter increases. Furthermore, the current carrying capacity is also dependent on the type of electrode; for instance, the current carrying capacity of pure tungsten electrodes is lower than alloyed tungsten electrodes.[4] The current would need to be increased for thicker samples in order to input enough heat to weld the extra material. As current applied increases up to about 200 amps, a water-cooled torch must be used instead of a gas-cooled torch in order to supply sufficient cooling to the electrode. The two different torches are pictured in Figure 1. In general, GTAW is used for the welding of butt, lap, edge, corner, and tee joints.[3] Some advantages of GTAW include: good weld bead control, high precision on the location and spread of the arc, and low spatter.[5]



(a) (b)

Figure 1: a) A gas-cooled GTAW torch allows the tungsten electrode to be cooled by the relatively cool shielding gas flow; b) a water-cooled GTAW torch feeds water through the torch in order to cool the electrode. The collet houses the electrode, which is threaded into the collet body which holds the collet and electrode in place. The cup is used to keep the flow of the shielding gas flowing toward the weld pool.[6]

During the GTAW process, it is important to be careful not to dip the tungsten electrode into the weld. By dipping the tungsten electrode into the weld, discontinuities and defects may be formed that impair the performance of the weld. These discontinuities, known as tungsten inclusions, embed particles of tungsten from the electrode into the weld.[4] As a result, the defects serve as an area of concentrated stress and lower the quality of the weld.

Gas Metal Arc Welding is a gas shielded-arc welding process that gains its welding heat from an arc between a consumable electrode and a workpiece. The electrode (which is also the filler wire and is generally of a similar composition to the metal being welded) is melted and transferred to the joint and fused to the workpiece by the arc. Like GTAW, the GMAW process requires a gas to shield the weld from the atmosphere. A high electrode current density is required for the metal from the electrode to be transferred to the workpiece. The power source of GMAW welding has "drooping volt-ampere characteristics"; the voltages of the machine decrease as the welding current increases. The electrode used is based on: "(1) the alloy matching the base metal, (2) metallurgical control of grain size, segregation, etc., (3) deoxidation, and (4) the assurance of arc stability and metal transfer characteristics."[3] Table II shows typical current ranges for different wire diameters. Some advantages of GMAW include its wire feeding capability which allows long weld beads to be deposited, its wide use as a robotic arc welding process, and its ability to be used in all positions.[5]

Table II. Typical Current Ranges for Different Wire Diameters Used in the GMAW Process

Electrode Diameter		Usable Current Range, A
mm	in.	
0.9	0.035	60–280
1.2	0.045	125–380
1.6	0.062	275–475

2.1.2 Base Metals

The chemical composition of A36 can be found in Table III. The AWS D1.1: Structural Welding Code for Steel as well as B4.0M: Standard Methods for Mechanical Testing of Welds and B2.1: Specification for Welding Procedure and Performance Qualification were used to qualify the A36 steel WPSs.[2,7,8]

Table III. Chemical Composition and Mechanical Properties of A36 Base Metal[9]

Alloy Element	C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Mg (%)	Cr (%)
A36	0.26 max	0.80 - 1.20	0.04 max	0.05 max	0.15 - 0.40 max	0.20	0	0

A36 is a low carbon steel alloy and is readily welded by all welding processes. It is used in the construction of bridges, buildings, oil rigs. gears, and machinery parts to name a few. Welds formed with A36 steel are of excellent quality and this makes it suitable for structural applications. Hardenability is defined as the ability of a material to form martensite, a microstructure that is prone to cold cracking when around a weld region. One method of predicting a material's hardenability is with the carbon equivalent (CE) formula. This formula equates the relative hardening contributions of a steel's constituents to the most significant hardening agent, carbon. However, it is generally believed that steels having low CE values are immune to weld cracking problems. The carbon equivalent of a steel is determined using Equation 1.[10]

$$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 \qquad \text{(Eq. 1)}$$

When welding A36 steel, it is important that the material is cleaned thoroughly before any welding begins. If the material is not cleaned, contaminants in the form of dirt, oil, oxides (in the form of corrosion), and surface treatments can easily form defects in the welded joint.

The high phosphorous and sulfur content in A36 steel (>.03%) make this material susceptible to hydrogen embrittlement after welding. Embrittlement of this material is due to the presence of hydrocarbons or water vapor during the welding process. To be sure that this does not occur, weld joints and adjacent areas must be cleaned before welding and the shielding gas must be placed over the weld pool properly during welding. A preheat or post-weld heat treatment may also help reduce the effects of hydrogen induced cracking.[11]

Any heat treatment and process history of the base metal should be documented; as different heat treatments react differently to the heat generated during the welding process (e.g. strain hardened materials lose all strength gained from the process near the weld).[11]

2.1.3 Electrodes and Filler Metals

The electrode tip configuration is a significant process variable for GTAW. When dc welding, the electrode tip is ground to a specific angle obtained by a process called grinding. Grinding is another shaping process; in this process the tip is ground with the axis of the electrode parallel to the spinning direction of the grinding wheel, which can be seen in Figure 2. The tip geometry affects the weld bead shape and size. As the tip angle increases, the weld penetration increases and the width of the weld bead decreases.[4] Furthermore, it is critical to keep the same electrode tip shape throughout an entire welding process because it can drastically change the weld bead shape and size.

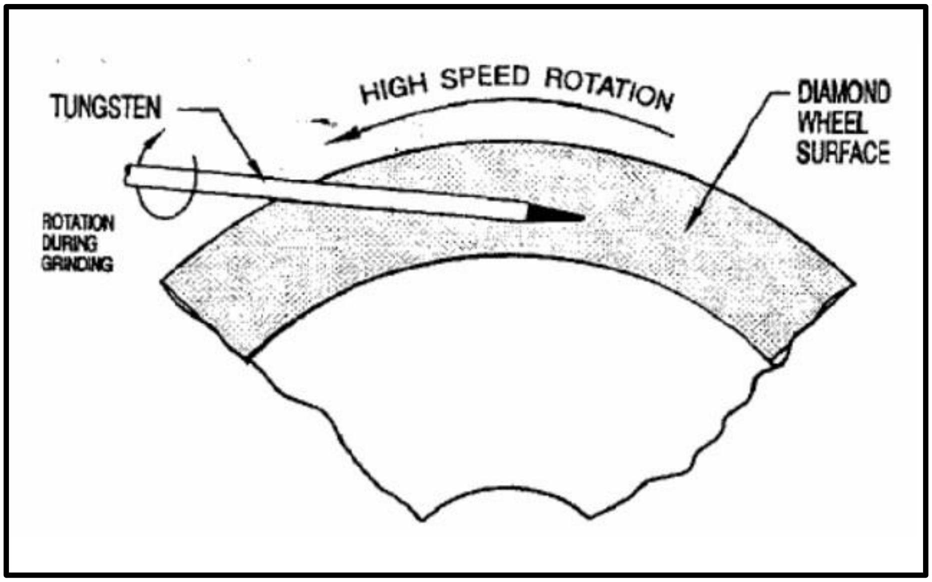


Figure 2: Tungsten electrodes are ground with the tip parallel to the rotating axis of a grinding wheel while the electrode is rotated to produce an even finish.

Selecting the right filler metal is important for both GMAW and GTAW welding. Specific filler metals are chosen based on their chemical composition which must be close to or matching the base metal composition. Filler rod diameters are selected depending on the type of metal transfer and base metal thickness.

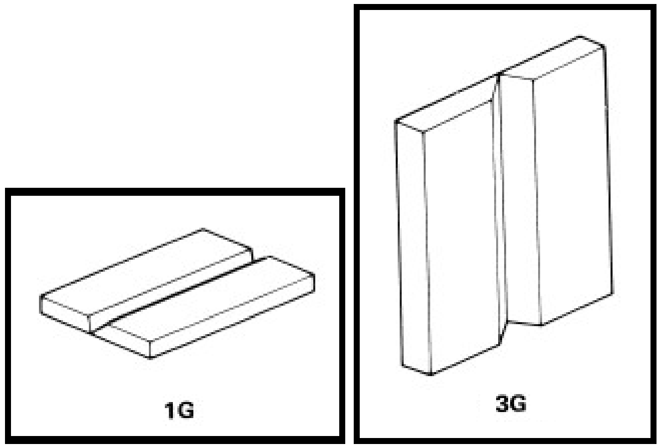
The filler metals used in this project were ER70S-2 and ER70S-6 for GTAW and GMAW, respectively. ER70S-2 and ER70S-6 are carbon steels alloyed with high amounts of silicon and manganese, which are both deoxidizers. Deoxidizers help prevent oxides from forming in the weld when welding with the highly reactive carbon dioxide shielding gas.[12] The mechanical properties of the filler metals, along with their corresponding base metals, are summarized in Table IV. The Certificates of Conformance from the supplier for ER70S-2 and ER70S-6 can be found in Appendix C and Appendix D, respectively.

Table IV. Tensile and Yield Strength of Base and Filler Metals

Filler/Base Metal	Tensile Strength (ksi)	Yield Strength (ksi)
A36 Steel [9]	58-80	36
ER70S-2 [12]	70 min.	58 min.
ER70S-6 [12]	72 min.	60 min.

2.1.4 Welding Positions

The positions used when welding for the qualification of the welding procedures were the 1G and 3G positions. The 1G position is shown in Figure 3a where the plate was laid flat and secured with clamps and tack welds; welding is then performed horizontally. The 3G position is shown in Figure 3b, where the plate is secured vertically and the weld is performed vertically.



(a) (b)

Figure 3: a) The 1G position of a grooved plate to be welded. The plate is both placed and welded horizontally; b) The 3G position of a grooved plate that will be welded. The plate is secured vertically and the weld will be made down the groove vertically, either from top to bottom or bottom to top.[13]

2.1.5 Shielding Gases and Gas Flow Rate

The effects of various shielding gas compositions on the weld bead shape for steel are shown in Figure 4. For this project, 100% argon gas was used for GTAW welding and a mix of 75% argon/25% CO_2 gas was used for GMAW welding. The 75% argon/25% CO_2 gas mixture was selected to minimize weld spatter of the weld puddle and produce a clean weld.

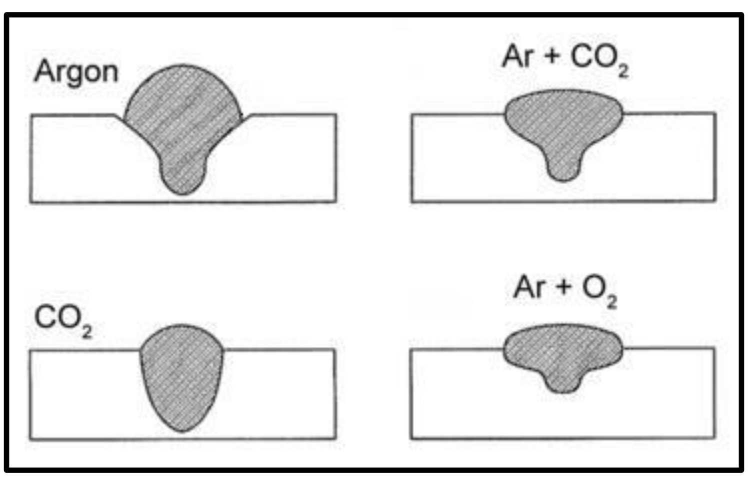


Figure 4: The effect of shielding gas composition on the weld penetration and bead shape for steel.[5]

The selection of gas flow rate depends on nozzle size and desired weld pool size. The gas flow rate increases proportionally to the cross-sectional area of the nozzle used in the welding torch. The typical shield gas flow rates for argon are 30 to 60 cfh (7 to 16 L/min.).[4]

2.2 Qualification

In order to qualify a WPS, the proposed weldment must demonstrate the mechanical properties required by the AWS standards. Test plates were welded according to the specified procedure by certified welders, which were then sectioned by flame cutting according to the diagram in Figure 5 as specified by AWS D1.1.[2] The ends of the test plates were discarded because they may have been welded at a different rate and tend to have higher impurity content than the rest of the weld bead.

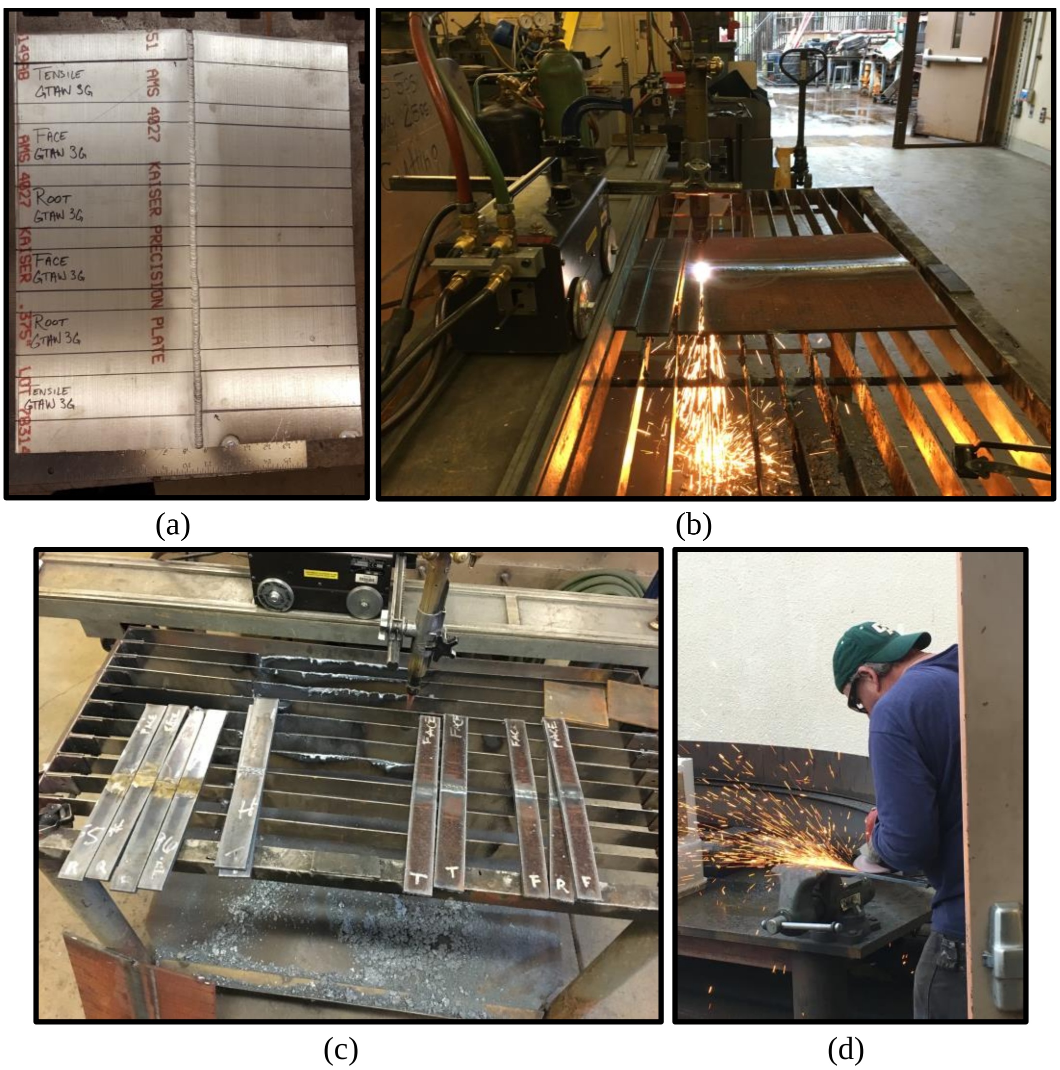


Figure 5: a) The plates were marked into test specimens according to AWS D1.1 and b) the sections were flame cut from the plates. c) The specimens were separated by test and d) the weld beads were ground flush using a grinding saw.

2.2.1 Procedure Qualification Record

Procedure Qualification Records (PQRs) are support documents for the WPS, which document the results of the tests required by the standards used. Required tests for this project's procedures include visual inspection, two root bend tests, two face bend tests, and two reduced section tensile tests as specified in AWS D1.1 and B2.1.[2,7] The bend tests were performed in accordance with ASTM E190-14 and the tensile tests were performed in accordance with ASTM A370-15. A PQR is typically signed by the visual inspector of the bend tests as well as the technician who performed the bend and tensile tests. An example WPS and PQR for the 3G GTAW process can be found in Appendix A and B, respectively.

2.2.2 Acceptance Criteria

Visual inspections were conducted prior to mechanical testing of the welds as a preliminary method of assessing the soundness of the weld. Visual inspection in the form of a dye penetrant test was performed on the welds after bend tests had been conducted to measure crack lengths within the weld region. Visual inspection of groove welds met the requirements set forth by AWS D1.1. In order to pass the tensile test, the strength of the weld shall not be less than the minimum specified tensile strength of the base metal or the weld metal (lower of the two). However, if the specimen breaks in the base metal outside of the weld or fusion line, then the test shall be accepted, provided the strength is not lower than 5% below the minimum specified tensile strength of the base metal.[14]

Passing the bend tests requires that the weld and heat affected zone, of a transverse weld-bend specimen, be completely within the bent portion of the specimen after testing. The guided-bend specimen shall not have open defects in the weld or heat affected zone larger than ⅛" in any direction on the convex surfaces after bending.[14]

2.3 Heat Affected Zone

The heat affected zone (HAZ) is the section of the base metal that was subjected to high enough temperatures caused by the welding process to affect the metallurgical structure. The microstructure of the HAZ is different than the pre-weld base metal microstructure and can be divided into 9 zones, some of which are illustrated in Figure 6:[15]

1. Complete mixing
2. Unmixed region
3. Partially melted
4. Grain coarsened region
5. Grain refined region
6. Partially transformed region
7. Spheroidized
8. Strain aged

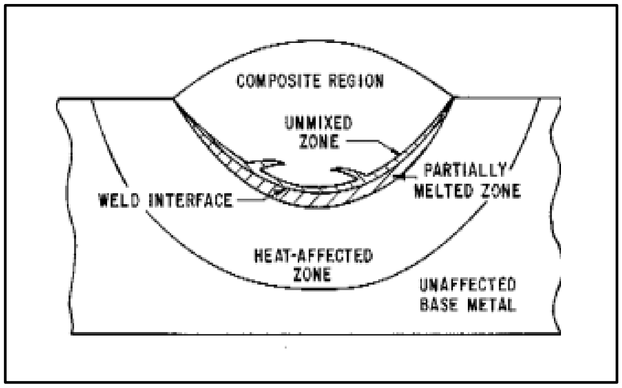


Figure 6: The Heat Affected Zone is the immediate area surrounding the weld that is mechanically affected by the heat of the welding process.

Additionally, the HAZ properties and microstructure are dependent on:[16]

- The rate of heat input and cooling
- The zone's peak temperature during the welding process
- Original grain size, grain orientation, and degree of prior cold work

The HAZ metallurgical characteristics directly influence the weld mechanical properties and joint performance. Smaller grains are formed from a system with lower current levels; the low levels of energy input encourage rapid cooling and a faster weld solidification rate. Inversely, with higher current and heat input, the cooling rate is slowed and coarse grains are produced. Therefore, a HAZ that has extremely large grains is an indication that high amperage or slow travel speed was used during welding. Coarser grains in the microstructure are typically a cause of lower hardness and lower tensile strength.[16]

2.4 Inclusions

Inclusions are compound materials that are introduced into the base metal during the manufacturing process. Too many inclusions may affect the mechanical properties of the base metal. There are two types of inclusion classifications: indigenous and exogenous. Indigenous inclusions are produced by reaction of metallic elements and elements such as oxygen, sulfur, carbon, nitrogen, etc. Furthermore, they can be caused by the cooling of the melt due to changes in solubility and are usually between 50-100 μm in size. Exogenous inclusions, on the other hand, come from sources like refractories or mold coatings that are outside the steel. These inclusions are usually visible to the naked eye on a polished section and are >100 μm in size.[17]

2.5 Porosity

Porosity is a large problem for welding and is one of the main causes for failures in welds. Porosity occurs in welds when a gas or water vapor, usually other than the shielding gas, is trapped within the weld during a welding pass. The trapped gas forms a pocket that serves as a stress riser that can reduce the mechanical properties of the weld. If water vapor is trapped instead, the vapor will expand as it is heated, potentially popping the pocket or at very least making it grow significantly. Porosity can also be a problem even if perfect shielding techniques are used because it is often intrinsic to the base metal itself. Porosity is easily spotted within a sectioned weld piece using optical or stereo microscopy techniques. Porosity can also be easily found within a weld prior to sectioning via radiographic interpretation techniques. These techniques are frequently used to determine the porosity levels, inclusion content, fusion problems, and cracking within the weld before testing, and therefore often save time and resources. Welded plates are often rejected if it is determined that the weld does not meet the quality requirements or if the defects exceed the allowable requirements of the standard.

3. Procedure

3.1 Preparation of the Specimens

All of the welding and preparation was done at Las Positas College. The bulk A36 plate was flame cut into 20" x 8" pairs of plates with 30° single V-grooves. A grinding saw was used to grind the flame cut portions flush and remove oxide from the vicinity of the groove. After tack welding the plates together, the welder welded the front (face) of the groove with 4 passes in either the 1G or 3G position. Between passes, the welder removed any oxide with a wire brush. Once the plates cooled, the backs (roots) of the grooves were back gouged with a burr and then root welded with one pass. Bend and tensile test specimens were flame cut from the plate (as seen in Figure 5 above) to analyze the welds' tensile strengths and ductility. They were prepared as per AWS D1.1 and the dimensions are given in Table V below.

Table V. Test Specimen Dimensions Post-Flame Cutting[2]

Dimension	Bend Specimens	Tensile Specimens
Length	16"	16"
Width	1.5"	2"
Thickness	0.38"	0.38"

After sectioning the specimens, the face of the weld was ground down flush with the base metal using a grinding saw and a belt grinder. The specimens to be tensile tested were milled to the recommended AWS and ASTM dimensions, as seen in Figure 7.[2]

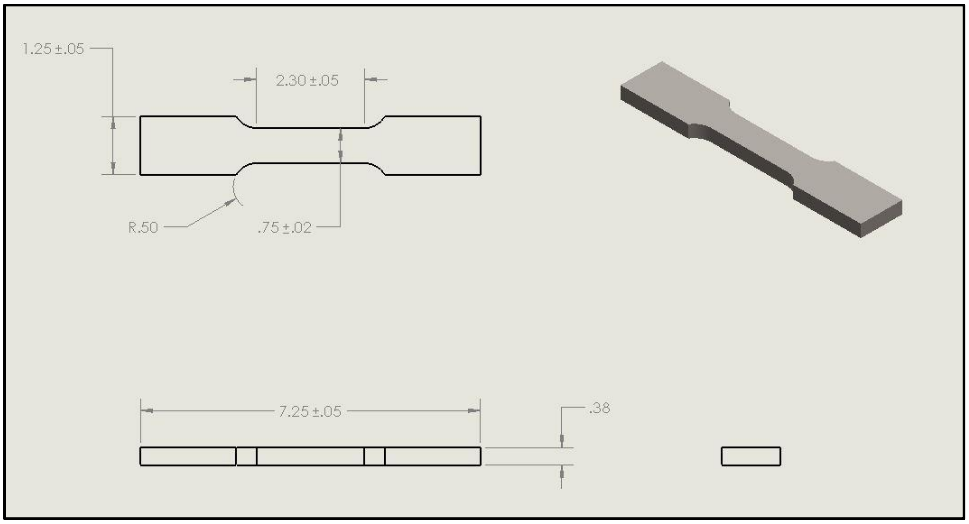


Figure 7: The tensile coupons were dimensioned as shown using a mill.

3.2 Testing

I. *Bend Test*

The bend test used was the wraparound method to measure the ductility of the weld and can be seen in Figure 8. The purpose of the bend test is to ensure the weld and base metal are properly fused and that the weld metal and HAZ have acceptable mechanical properties. Furthermore, when defects in the material exist while being exposed to high strains from the bend test, the material can tear locally and may result in a specimen failure.[18] AWS D1.1 required two face bend and two root bend tests per welding process. These test samples were accepted if no cracks longer than 1/8" were present within the weld region after bending.

Figure 8: The mechanical wraparound bend test measures the ductility of a weld.

II. *Reduced Section Tensile Test*

An Instron tensile testing machine was used to find the ultimate tensile strength (UTS) of the specimens. The AWS code required at least two specimens from the same plate to exceed a minimum UTS of 58 ksi if the failure occurred in the weld, or 55.1 ksi if the failure occurred outside of the weld. A reduced section weld specimen can be seen being tensile tested in Figure 9.

Figure 9: The reduced section tensile test measured the tensile strength of a welded sample.

III. *Optical Microscopy*

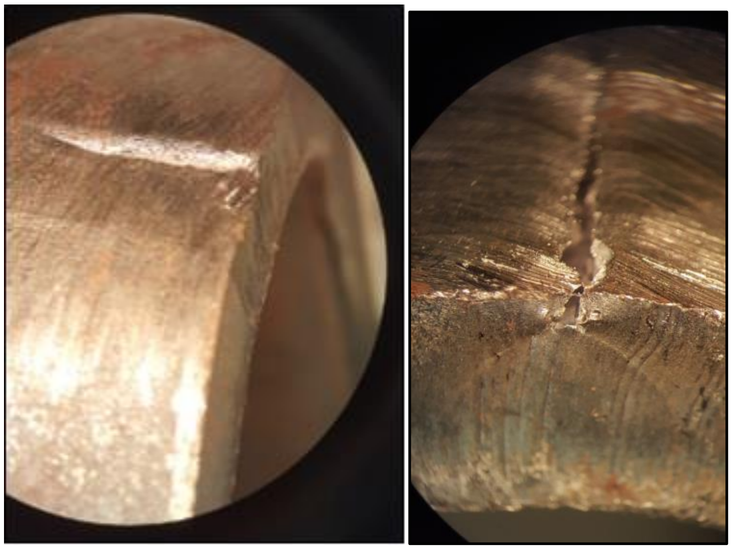
Optical microscopy examination was performed on samples in the as-polished and etched conditions. The samples were inspected in the as-polished condition in order to determine the inclusion type, inclusion content, and porosity levels in the base and weld metal. The samples in the etched condition were inspected to determine the microstructure of the base metal and to evaluate the microstructure of the heat affected zone and weld metal.

IV*. Scanning Electron Microscopy*

A scanning electron microscope (SEM) was used to determine the mechanism of failure within the cracks as well as gain an enhanced view of the failures. Energy dispersive X-ray spectroscopy (EDS) was attempted in order to determine the composition of various inclusions and oxides present and observed under metallographic and fractographic examination, however, the results were inconclusive.

V. *Stereo Microscopy*

The specimens that failed the bend test, shown in Figure 10, were submerged in liquid nitrogen and broken along the crack length. A stereo zoom microscope was used to inspect the fractured surfaces of the bend test cracks. The fractographic method aided in determining the causes of failure in the welds.

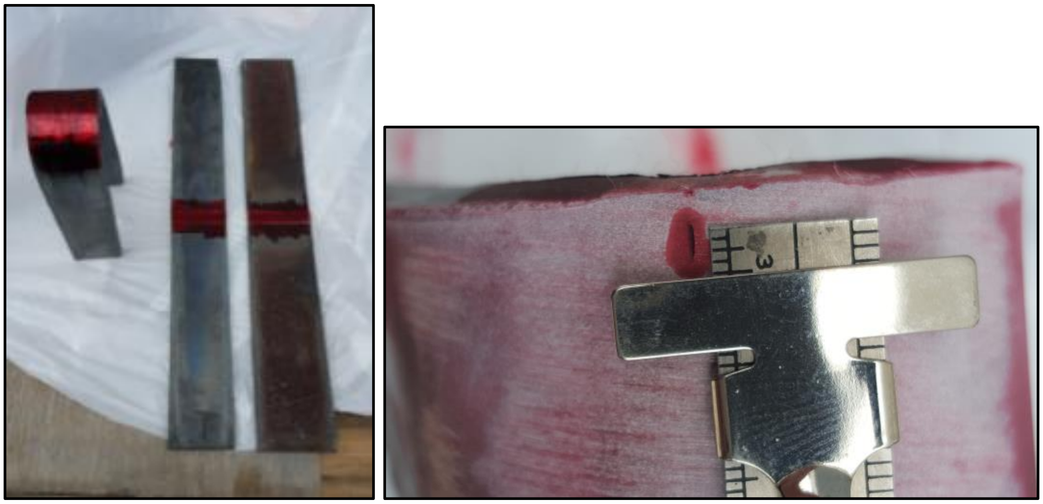


(a) (b)

Figure 10: Images of failed bend specimen; a) GMAW 1G bend failure and b) GTAW 1G bend failure.

VI. *Dye Penetrant Visual Inspection*

Dye penetrant inspection (DPI) is a nondestructive test method that aids in detecting any flaws that are open to the surface of a test piece. Dye penetrant inspection was performed on each sample that was bend tested, shown in Figure 11. The outside convex surface of the bent specimens was coated with a red dye and given a sufficient amount of time for the dye to penetrate any surface cracks. The surface was then wiped clean and coated with a white developer to extract the red dye from any flaw present on the weld surface via capillary action.



(a) (b)

Figure 11: Dye penetrant inspection was performed on both bend tested specimen and specimen in the as welded condition, (a) application of the penetrant and (b) after applying the developer to aid in the discovery of cracks.

4. Results

4.1 Mechanical Tests

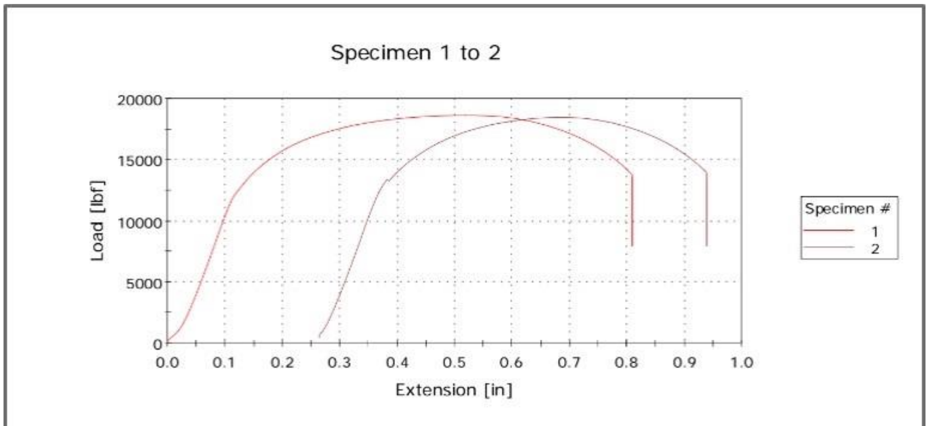
I. *Bend Test*

The bend tests performed resulted in at least one bend test failing for each process except for the 3G GTAW. All four bend specimens taken from a single plate must pass bend tests for a procedure to pass. The 3G GTAW was therefore the only plate that passed bend tests, shown in Figure 12, and thus the only process that could be qualified.

Figure 12: Passed GTAW 1G bend specimen.

II. *Tensile Test*

Tensile tests were performed on only the 3G GTAW process plate. The tensile test results showing maximum loads and extension for each of the tested samples is shown in Figure 13. The ultimate tensile strengths of the samples were calculated using the maximum load and the original area of the reduced section of the tensile tests according to Equation 2.



	Maximum Load [lbf]
1	18623.95104
2	18464.75120

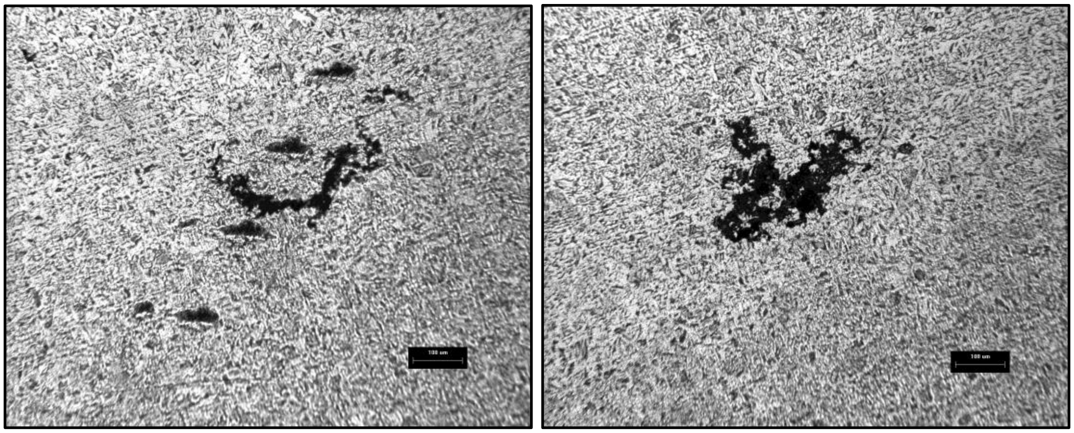
Figure 13: The reduced section tensile test curves of the 3G GTAW process samples are shown. The second test has been offset for clarity.

$$UTS = \frac{MAXIMUM\ LOAD}{ORIGINAL\ LOAD} \qquad \text{(Eq. 2)}$$

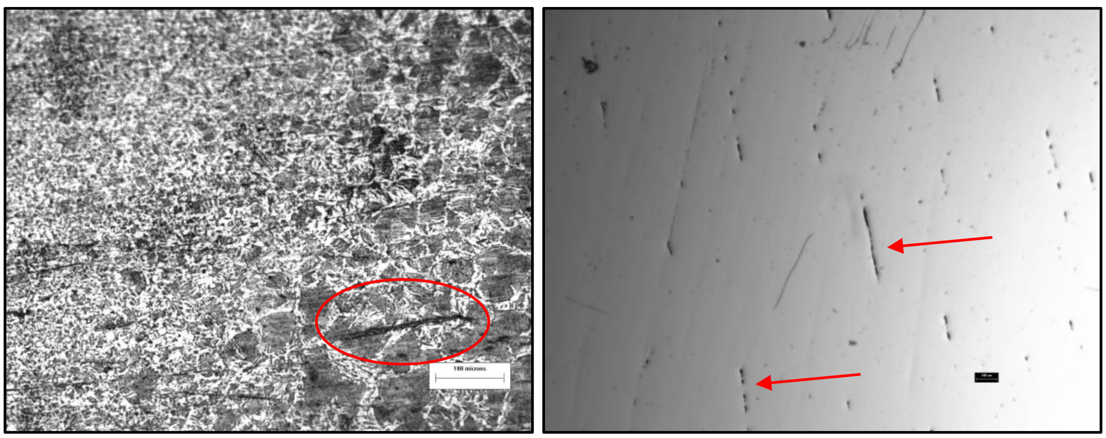
The ultimate tensile strength of sample 1 was calculated to be 66.2 ksi; sample 2 was calculated to be 65.65 ksi. Both tests broke outside of the weld region and therefore passed the required minimum tensile strength of 55.1 ksi. The 3G GTAW plates passed all required bend and tensile tests, therefore, this procedure was qualified.

4.2 Inclusion Examination

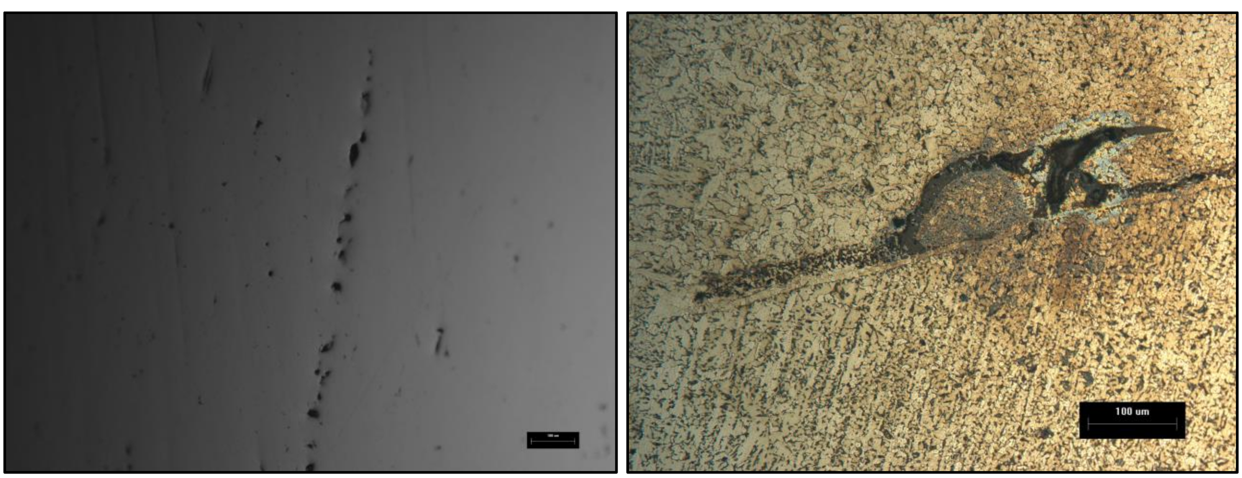
Heavy inclusion content was found in both the base metal as well as the welded region and HAZ of the samples. After microscopic examination and comparative analysis, it was determined that the inclusions consisted of aluminas, silicates, sulfides, and globular oxides.[19] It would be safe to assume that the heavy inclusion content found in the examined samples varied only slightly in the rest of the plate because each welded plate was originally cut from the same larger plate. Examples of these inclusions can be seen in Figure 14.



(a) Silica inclusions found in the base metal of a 1G GMAW sample.



(b) Silicate inclusions found in the grain coarsened region of the heat affected zone (left) and the base metal of a 1G GTAW sample (right).

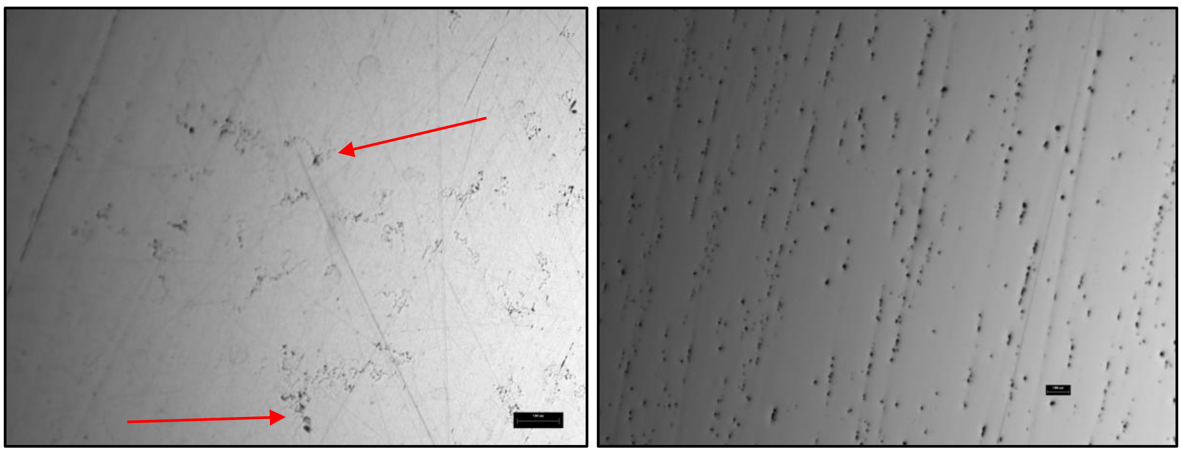


(c) Globular oxide inclusions in the base metal (left) and weld/base metal interface (right) in a 1G GMAW sample.

Figure 14: Various inclusions are shown: a) shows examples of large oxide inclusions; b) shows silicate inclusions; and c) shows globular oxide inclusions as well as oxide inclusions along the weld interface.

4.3 Porosity

Elevated amounts of porosity were observed in the weld metal. This may have been caused by a few different reasons: the base metal may have been wet prior to welding, causing the water to expand on heating and form gas pockets; lifting the tungsten electrode too far away from the workpiece which may have caused turbulence in the shielding gas, allowing other gases to penetrate the weld; or moisture in the gas line itself may have been released with the shielding gas. The crack after the bend test was split open by submerging the sample in liquid nitrogen. This exposed the fracture faces of the cracks present after the bend test. The surfaces were examined under the stereo zoom scope. This was most likely the cause for bend test failure and porosity in the weld metal of a 1G GMAW sample. Figure 15 shows examples of large porosity in the form of gas pockets in a failed 1G GTAW bent sample.



(a) (b)

Figure 15: Weld metal porosity in the form of a) macroporosity present throughout the base metal and b) small gas pockets in the weld metal of a 1G GMAW sample.

4.4 Heat Affected Zone

The HAZ microstructure of the 1G GMAW process reveals large grains as a result of high heat input used while welding. This is most likely due to high amperage, high voltage, and/or low travel speeds. As mentioned previously, large grains can cause lower hardness and tensile strength due to the ability of dislocations to move farther within the grains. The coarsening of the grains can be seen in Figure 16 and Figure 14b.

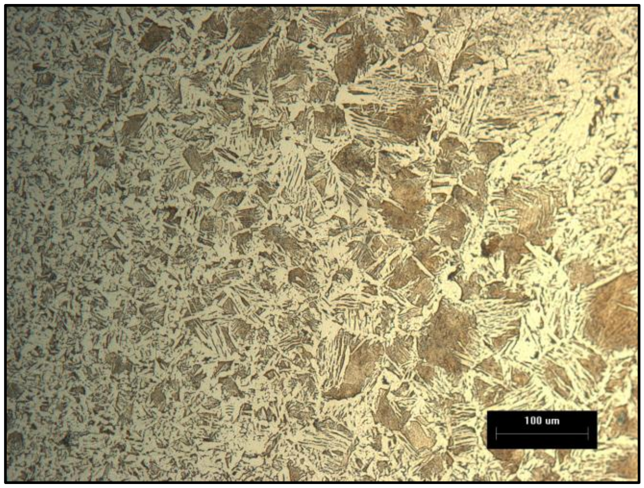


Figure 16: The Heat Affected Zone of the weld is shown.

4.5 Oxide

A fractograph of the 1G GMAW process was taken for failure analysis. Figure 17 reveals multiple features responsible for the failure of the GMAW process. Oxide between weld passes was an indication of poor cleaning. The grey charred region was evidence of a lack of shielding gas or moisture included with the shielding gas. Visibility of the base metal lamellar structure indicated lack of fusion. The pin holes were possibly caused by shielding gas being trapped and expanding within the weld, or from original porosity in the base metal. Gas pockets in base metal can have oxygen trapped and can cause blowouts.

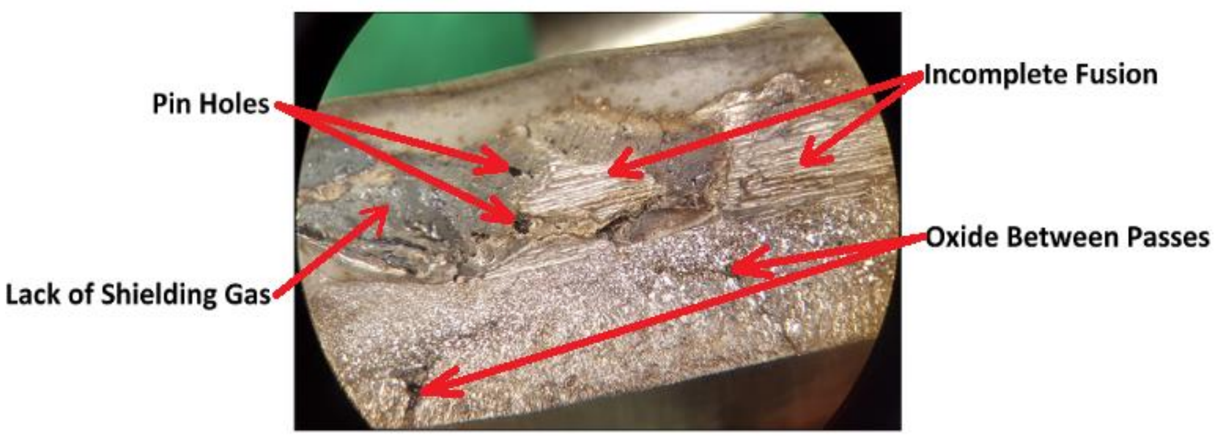
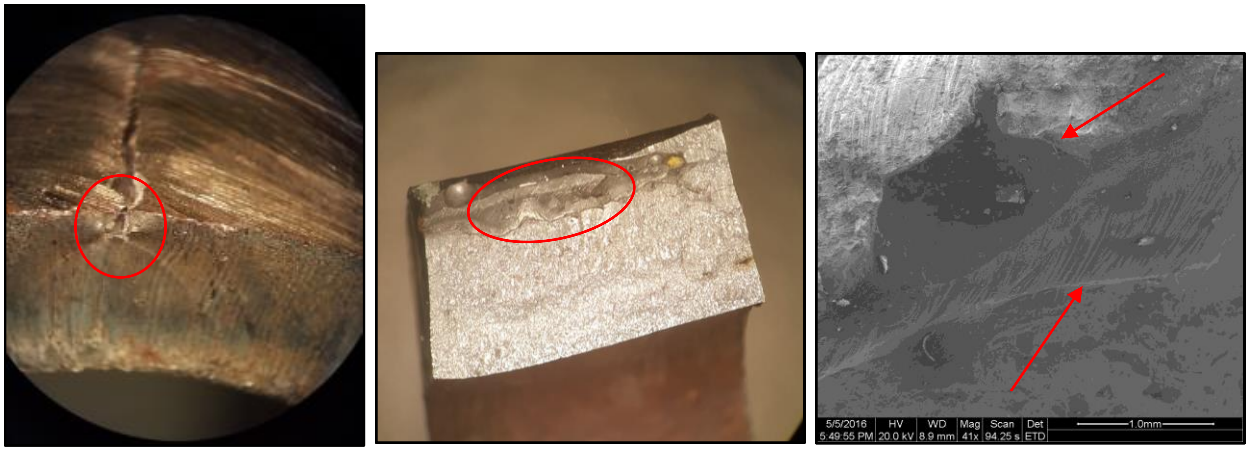


Figure 17: A fractograph of a 1G GMAW sample that shows signs of porosity via pin holes, a lack of shielding gas via the charred look of the metal, incomplete fusion in the form of lamination, and improper cleaning techniques in the form of oxide between passes.

4.6 Lack of Penetration and Fusion

There was evidence of lack of penetration and lack of fusion in the 1G GTAW process and are the main source of failure for this specimen. The initial face weld did not penetrate through to the root side of the plate and the crack propagated along the root face of the weld. The bend specimen was fractured and analyzed, as shown in Figure 18.



(a) (b) (c)

Figure 18: a) Transverse view of the GTAW 1G weld revealed lack of penetration, b) Fractograph revealed gas pockets, lack of filler metal, and lack of fusion, and c) SEM image confirms a gas pocket next to grind marks along the weld metal from preparation, indicating a lack of fusion between the filler and base metal.

5. Conclusion and Recommendations

The completion of this project met the following goals: the qualification of a WPS, the provision of recommendations to prevent future process failure, and an outline to advance and facilitate future senior project work. The GTAW process for A36 steel in the 3G position passed all required visual and mechanical tests as specified by AWS D1.1. Therefore, the WPS of the aforementioned process was qualified for use by Las Positas College to train and certify their students. GMAW process failures were due to problems with the base metal and problems with the welding technique. Base metal problems were porosity, inclusions, and laminations; and welding technique problems included lack of shielding gas, lack of fusion, silicate and oxide deposits, and high heat input. The 1G GTAW failure was due to poor welding technique. Problems with the welding technique included lack of penetration, lack of fusion, and large gas pockets. Future attempts to qualify the WPSs for A36 steel of the GMAW and GTAW processes in the 1G position should be conducted with the following recommended changes to the procedure;

Highly Recommended

1. Preheat the base metal to under 400°F in order to remove any moisture that may cause micro porosity and hydrogen embrittlement (for base metal stored in wet or humid environments).

2. Lower weld travel speed to ensure full weld penetration as well as complete fusion between the base metal and filler metal.
3. Thoroughly clean weld surface between weld passes with wire brush or wire wheel and wipe with acetone to remove oil and rust residue.
4. Decrease the process heat input by (a) decreasing the process voltage or current, (b) maintain a weld interpass temperature less than 400°F, and (c) section the test coupons with vertical saw instead of flame cutting. All of which decrease weld spatter, undercut, and grain coarsening in the HAZ.

Optional (if budget permits)

5. Purchase or install an online gas dryer to remove moisture in the shielding gas.
6. Switch from a Single V-groove to a Double V-groove to achieve better or complete penetration and avoid the need of back gouging.
7. Weld mock up sample plates to establish welding parameters before any actual plates for qualification are welded.
8. If procedures fail consistently, consider sending welded plate for x-ray testing prior to sectioning of plate to detect any imperfections within the base metal or the weld metal.
9. For GMAW of A36 steel consider using ER70S-3 filler rod for base metal with moderate to high inclusion content.
10. Purchase a material with an inclusion severity level of 2 and types A, B, C, and D series. See Appendix E for a chart used to determine inclusion type and severity.

Future senior projects should attempt to qualify a maximum of 2-3 WPSs and further research the effects of inclusion content. A common method of determining the nature of non-metallic inclusions and aid in inclusion classification is Energy Dispersive Spectroscopy (EDS).

ACKNOWLEDGEMENTS

The WPS and PQR for the 3G GTAW procedure was approved by Regan Rumph, Brecken DeOilers, and Neri Lupian, who performed and evaluated the results of the bend and tensile test. The final approval of the WPS/PQR was performed by Mr. Scott Miner who is a certified weld inspector and instructor at Las Positas College in Livermore, California. Mr. Miner was also the sponsor for this project.

The bend tests were performed using equipment of Las Positas welding college facilities. The tensile test, metallographic and fractograph analysis was performed using equipment and facilities of the Cal Poly Materials Science and Engineering Department.

6. References

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7. Appendices

Appendix A - Qualified Welding Procedure Specification: 3G GTAW A36

ANNEX N AWS D1.1/D1.1M:2010

WELDING PROCEDURE SPECIFICATION (WPS) Yes ■
PREQUALIFIED ______ QUALIFIED BY TESTING ______
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ■

Identification # GTAW – LPC – 01 – GTAW 3G
Revision Ø Date 5/23/16 By SM
Authorized by SM Date 5/23/16
Type—Manual ■ Semiautomatic ☐
Mechanized ☐ Automatic ☐

Company Name LAS POSITAS COLLEGE
Welding Process(es) GTAW
Supporting PQR No.(s) -

JOINT DESIGN USED
Type: V- GROOVE
Single ■ Double Weld ☐
Backing: Yes ☐ No ■
Backing Material:
Root Opening ______ Root Face Dimension 1/16"
Groove Angle: 60° Radius (J–U) ______
Back Gouging: Yes ■ No ☐ Method GRINDER

BASE METALS
Material Spec. ASTM A36
Type or Grade A36
Thickness: Groove 3/8" Fillet ______
Diameter (Pipe) ______

FILLER METALS
AWS Specification A5.18
AWS Classification ER70S-2

SHIELDING
Flux ______ Gas ARGON
Composition 100
Electrode-Flux (Class) ______ Flow Rate 20-25 CFH
Gas Cup Size No. 8

PREHEAT
Preheat Temp., Min. ______
Interpass Temp., Min. ______ Max. 350°

POSITION
Position of Groove: ALL Fillet: ______
Vertical Progression: Up ■ Down ☐

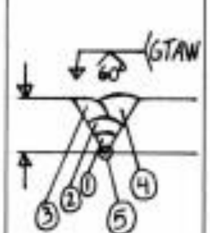
ELECTRICAL CHARACTERISTICS
Transfer Mode (GMAW) Short-Circuiting ☐
Globular ☐ Spray ☐
Current: AC ☐ DCEP ☐ DCEN ■ Pulsed ☐
Power Source: CC ■ CV ☐
Other ______
Tungsten Electrode (GTAW)
Size: 3/32"
Type: EWCe -2

TECHNIQUE
Stringer or Weave Bead: STRINGER
Multi-pass or Single Pass (per side) MULTI-PASS
Number of Electrodes 1
Electrode Spacing Longitudinal ______
Lateral ______
Angle ______
Contact Tube to Work Distance ______
Peening ______
Interpass Cleaning: WIRE BRUSH/ WIRE WHEEL

POSTWELD HEAT TREATMENT
Temp. ______
Time ______

WELDING PROCEDURE

Pass or Weld Layer(s)	Process	Filler Metals		Current		Volts	Travel Speed	Joint Details
		Class	Diam.	Type & Polarity	Amps or Wire Feed Speed			
ALL	GTAW	ER70S-2	3/32"	DCEN	90-125 A	25-30 V	4-8 ipm	



Form N-1 (Front)

354

Appendix B - WPS Procedure Qualification Record: 3G GTAW A36

ANNEX N

AWS D1.1/D1.1M:2010

Procedure Qualification Record (PQR) # LPC01
Test Results

TENSILE TEST

Specimen No.	Width	Thickness	Area	Ultimate Tensile Load, lb	Ultimate Unit Stress, psi	Character of Failure and Location
1	0.75	0.375	0.28125	18624	66.22	Ductile, Base Metal
2	0.75	0.375	0.28125	18464	65.65	Ductile, Base Metal

GUIDED BEND TEST

Specimen No.	Type of Bend	Result	Remarks
1	Face	Pass	
2	Face	Pass	
3	Root	Pass	
4	Root	Pass	

VISUAL INSPECTION
Appearance ____
Undercut ____
Piping porosity ____
Convexity ____
Test date 3/5/16
Witnessed by S. Miner

Radiographic-ultrasonic examination
RT report no.: ____ Result ____
UT report no.: ____ Result ____

FILLET WELD TEST RESULTS
Minimum size multiple pass Macroetch
1. ____ 3. ____
2. ____
Maximum size single pass Macroetch
1. ____ 3. ____
2. ____

Other Tests

All-weld-metal tension test
Tensile strength, psi ____
Yield point/strength, psi ____
Elongation in 2 in, % ____
Laboratory test no. ____

Welder's name BALBIR GAKHAL
Clock no. ____ Stamp no. ____
Tests conducted by LAS POSITAS COLLEGE / CAL POLY MATE Laboratory
Test number LPC01
Per AWS D1.1, B4.0

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in conformance with the requirements of Clause 4 of AWS D1.1/D1.1M, (2010) *Structural Welding Code—Steel.*
(year)

Scott A Miner
CWI 13090221
QC1 EXP. 9/1/2016

Signed ____
Manufacturer or Contractor
By SCOTT A MINER
Title CWI / CWE
Date 5/23/2016

Form N-1 (Back)

358

Appendix C - ER70S-2 Certificate of Conformance

The Lincoln Electric Company
22801 St. Clair Avenue
Cleveland, Ohio 44117-1199

CERTIFICATE OF CONFORMANCE

(APPLIES ONLY TO U.S. PRODUCTS)

LINCOLN ELECTRIC
THE WELDING EXPERTS®
[1Year]

Product:	Lincoln® ER70S-2
Classification:	ER70S-2
Specification:	AWS A5.18:2005, ASME SFA-5.18
Date	May 21, 2015

This is to certify that the product named above and supplied on the referenced order number is of the same classification, manufacturing process, and material requirements as the material which was used for the test that was concluded on the date shown, the results of which are shown below. All tests required by the specifications shown for classification were performed at that time and the material tested met all requirements. It was manufactured and supplied according to the Quality System Program of the Lincoln Electric Company, Cleveland, Ohio, U.S.A., which meets the requirements of ISO9001, NCA3800, AWS A5.01, and other specification and Military requirements, as applicable. The Quality System Program has been approved by ASME, ABS, and VdTUV.

Operating Settings		RESULTS
Electrode Size		1/8 inch
Polarity	DC-	DC-
Shielding Gas (per AWS A5.32)	100% Ar (I1-Ar-100)	100% Ar (I1-Ar-100)
Voltage, V		16
Current, A		280
Travel Speed, cm/min (in/min)		13 (5)
Pass/Layers		22/7
Preheat Temperature, °C (°F)		135 (275)
Interpass Temperature, °C (°F)		150 (300)
Postweld Heat Treatment	As-welded	As-welded
Mechanical properties of weld deposits		
Tensile Strength, MPa (ksi)	(70 min.)	590 (86)
Yield Strength, 0.2% Offset, MPa (ksi)	(58 min.)	520 (75)
Elongation %	22 min.	31
Average Impact Energy Joules @ -29 °C (ft-lbs @ -20 °F)	(20 min.)	406 (300) 362,425,432 (267,314,318)
Average Hardness, HRB	Not Required	89

Electrode composition (weight %)		Electrode Results
C	0.07 max.	0.06
Mn	0.90 - 1.40	1.10
Si	0.40 - 0.70	0.52
S	0.035 max.	0.004
P	0.025 max.	0.004
Cr	0.15 max.	0.04
Ni	0.15 max.	0.03
Mo	0.15 max.	0.01
V	0.03 max.	0.00
Total Cu	0.50 max.	0.15
Ti	0.05 - 0.15	0.11
Al	0.05 - 0.15	0.10
Zr	0.02 - 0.12	0.06

1. This certificate complies with the requirements of EN 10204, Type 2.2.
2. The electrode size required to be tested for this classification is 1/8 inch. All other sizes manufactured will also meet these requirements.
3. Test assembly constructed of ASTM A36 steel.
4. Radiographic Inspection: Met requirements.
5. Results below the detection limits of the instrument or lower than the precision required by the specification are reported as zero. Strength values in SI units are reported to the nearest 10 MPa converted from actual data. Preheat and interpass temperature values in SI units are reported to the nearest 5 degrees.

Toronto Cunningham — May 21, 2015
Toronto Cunningham, Certification Supervisor — Date

David A. Fink — May 21, 2015
Dave Fink, Manager, Compliance Engineering, Consumable R&D — Date

Appendix D - ER70S-6 Certificate of Conformance

The Lincoln Electric Company
22801 St. Clair Avenue
Cleveland, Ohio 44117-1199

CERTIFICATE OF CONFORMANCE

(APPLIES ONLY TO U.S. PRODUCTS)

LINCOLN ELECTRIC
THE WELDING EXPERTS®

Product:	Lincoln® ER70S-6
Classification:	ER70S-6
Specification:	AWS A5.18:2005, ASME SFA-5.18
Date	June 25, 2013

This is to certify that the product named above and supplied on the referenced order number is of the same classification, manufacturing process, and material requirements as the material which was used for the test that was concluded on the date shown, the results of which are shown below. All tests required by the specifications shown for classification were performed at that time and the material tested met all requirements. It was manufactured and supplied according to the Quality System Program of the Lincoln Electric Company, Cleveland, Ohio, U.S.A., which meets the requirements of ISO9001, NCA3800, AWS A5.01, and other specification and Military requirements, as applicable. The Quality System Program has been approved by ASME, ABS, and VdTUV.

Operating Settings		RESULTS
Electrode Size		1/8 inch
Polarity	DC-	DC-
Shielding Gas (per AWS A5.32)	100% Ar (I1-Ar-100)	100% Ar (I1-Ar-100)
Voltage, V	16 - 19	16
Current, A	250 - 280	265
Travel Speed, cm/min (in/min)	(4 - 6)	13 (5)
Pass/Layers		16/8
Preheat Temperature, °C (°F)	(275 min.)	135 (275)
Interpass Temperature, °C (°F)	(325 max.)	150 (300)
Postweld Heat Treatment	As-welded	As-welded
Mechanical properties of weld deposits		
Tensile Strength, MPa (ksi)	(70 min.)	590 (86)
Yield Strength, 0.2% Offset, MPa (ksi)	(58 min.)	450 (65)
Elongation %	22 min.	31
Average Impact Energy Joules @ -29 °C (ft-lbs @ -20 °F)	(20 min.)	See Note 446,446,450 (329,329,332)
Average Hardness, HRB	Not Required	88

Electrode composition (weight %)		1/8 Electrode Results
C	0.06 - 0.15	0.09
Mn	1.40 - 1.85	1.46
Si	0.80 - 1.15	0.87
S	0.035 max.	0.001
P	0.025 max.	0.005
Cr	0.15 max.	0.03
Ni	0.15 max.	0.01
Mo	0.15 max.	0.00
V	0.03 max.	0.00
Total Cu	0.50 max.	0.15

NOTE: One or more of the reported impact values exceeds the machine capacity (542 J or 400 ft-lbs) or is greater than its 80% capacity (434 J or 320 ft-lbs). The values reported are approximate and should not be averaged, per ASTM E23.

1. This certificate complies with the requirements of EN 10204, Type 2.2.
2. The electrode size required to be tested for this classification is 1/8 inch. All other sizes manufactured will also meet these requirements.
3. Test assembly constructed of ASTM A36 steel.
4. Radiographic Inspection: Met requirements.
5. Results below the detection limits of the instrument or lower than the precision required by the specification are reported as zero. Strength values in SI units are reported to the nearest 10 MPa converted from actual data. Preheat and interpass temperature values in SI units are reported to the nearest 5 degrees.

June 25, 2013
Toronto Cunningham, Certification Supervisor — Date

June 25, 2013
Dave Fink, Manager, Compliance Engineering, Consumable R&D — Date

Page 1 of 1 — Cert. No. 9150

Appendix E - Determining Inclusion Type and Severity[17]